

**A Computer Simulation Model: Construction Analysis
for Pavement Rehabilitation Strategies (CA4PRS)**

Report Prepared for

CALIFORNIA DEPARTMENT OF TRANSPORTATION

By

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EXECUTIVE SUMMARY

Most state highways in the United States were built during the infrastructure construction boom of the 1960's and 1970's with an investment of more than \$1 trillion. They have now exceeded their 20-year design lives and are seriously deteriorated. The consequences are high maintenance and road user costs because of degraded road surfaces and construction work zone delays. These drawbacks demonstrate the need for efficient planning of highway closures for rehabilitation.

This paper presents a computer simulation model, CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies), that helps estimate the maximum amount (distance) of highway that can be rehabilitated or reconstructed within various closure timeframes. The software model balances numerous constraints such as scheduling interfaces, pavement materials and design, contractor logistics and resources, and traffic operations. The software has been successfully used on several urban freeway rehabilitation projects with high traffic volume in California, including the I-10 Pomona and I-710 Long Beach projects. CA4PRS helps transportation agencies and contractors plan highway rehabilitation strategies by taking into account long-life pavement performance, construction productivity, traffic delay and total cost.

1. INTRODUCTION

1.1 Paradigm Change in Highway Construction

About 256,000 km of the National Highway System (NHS), which is four percent of the American road network (US Census Bureau 1994), carries 40 percent of auto travel and 75 percent of truck traffic. It also connects 90 percent of the households and businesses in the nation (FHWA 1996). Many of the pavements on these highways, constructed during the infrastructure construction boom in the 1960's and 1970's, have exceeded their design lives in less than 20 years due to continuously increasing traffic demand. This is evidenced by the fact that over the last 20 years highway traffic has increased by 75 percent while highway facilities have expanded by only 4 percent during the same period (Herbsman and Glagola 1998).

In recent years state transportation agencies have shifted their focus from building new transportation facilities to "4-R" projects: restoration, resurfacing, rehabilitation and reconstruction. This shift in emphasis was driven by studies which show that maintaining federal-aid highways in their current physical condition has a financial rate of return of about 30 to 40 percent, while constructing new highways has a rate of return generally lower than 10 percent (US Congressional Budget Office@1988). Further complicating rehabilitation project is that roughly 30 percent of these 4-R type highway rehabilitation projects were located in urban areas in 1999-2001, where construction caused serious problems with traffic service for the communities that used these freeways (Existing Highways@ 2002).

1.2 Innovative Highway Rehabilitation in California

The State of California, a pioneer in highway construction, is facing deteriorated highway infrastructure on a large scale. More than 90 percent of the 78,000 lane-km of the state highway system was built between 1955 and 1970 with 20-year design lives. This significant state of degradation adversely affects road-user safety and ride quality, and causes high vehicle operating and highway maintenance costs. In 1998, the California Department of Transportation (Caltrans) initiated the Long-Life Pavement Rehabilitation Strategies (LLPRS) program to rebuild approximately 2,800 lane-km of deteriorated urban freeways over the next 10 years. The program represented an estimated \$1 billion investment over and above the regular State Highway Operation and Protection (SHOP) budget (Caltrans 1998). LLPRS candidate projects were selected based upon criteria of poor pavement structural condition and ride quality and a minimum 150,000 Average Daily Traffic (ADT) or 15,000

Average Daily Truck Traffic. Most of the candidate freeways were Portland Cement Concrete (PCC) paved interstates in the Los Angeles Basin (80 percent) and the San Francisco Bay Area (15 percent).

Traditionally, urban freeway rehabilitation or reconstruction projects in California have used 7- or 10-hour nighttime closures because daytime closures cause unacceptable delays to weekday peak travel. The disadvantage of nighttime closures is that they may lead to poor construction quality control which, in turn, may affect pavement life expectancy and pavement surface smoothness, and jeopardize the safety of road users and construction crews (Lee 2000). Nighttime closures may also result in longer total closure times, higher construction and traffic handling costs, and greater traffic delay to road users. In recognition of these drawbacks, Caltrans has adopted innovative highway rehabilitation strategies of accelerated construction with continuous (round-the-clock) operations during 55-hour weekend or 72-hour weekday closures for LLPRS projects.

1.3 Research Motivation and Approach

The increased need for highway maintenance and rehabilitation has led to much research on construction methods and their impact on traffic flow. However, no systematic research has been conducted, until now, with the goal of integrating pavement materials and design, construction logistics, and traffic operations. These issues are clearly essential to determine the most economical rehabilitation strategies (Anderson and Russell 2001). For rehabilitation of high volume urban freeways, three competing goals should be satisfied:

- the pavement should have a service life of at least 30 years,
- construction schedules should be fast, and
- traffic delays resulting from construction closures should be minimized.

To meet design life and constructability goals, pavement design must focus on 1) thinner structural sections and 2) materials and curing times that can shorten construction without sacrificing quality and performance (Roesler et al. 1999). Construction planning should focus on hastening the construction process and making it more predictable by incorporating such concepts as contingency (risk) management, incentives/disincentives (I/D), and cost plus schedule (A+B) bidding (Arditi et al. 1997). Traffic planning should focus on minimizing traffic delay impact without sacrificing construction productivity.

The integrated analysis of design, construction, and traffic requires a construction production analysis model to provide a schedule baseline for highway rehabilitation projects. The CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) software, described in this paper, is

such a scheduling tool and was designed for constructability analysis of highway rehabilitation projects (Technology/Business Opportunity: CA4PRS@ 2003). It is a knowledge-based computer simulation model designed to help transportation agencies and paving contractors make sound construction project management decisions at each stage of the highway rehabilitation project: planning, design, and construction.

The input variables of CA4PRS are schedule interfaces, pavement design and materials, resource constraints, and lane closure schemes. These were identified by experienced Caltrans engineers and the research team. The model's formulation was reviewed and adjusted through technical committee meetings with the Southern California Chapter of the National Asphalt Pavement Association (NAPA) and the Western States Chapter of the American Concrete Pavement Association (ACPA). The software was tested on projects throughout California. Such tests also allowed us to gather construction resource and schedule activity relationship data to calibrate and validate the software. Details of these case studies are described later in this paper.

1.4 Research Relevance and Applicability

The CA4PRS model was developed to provide road agencies and the transportation industry with a systematic construction engineering and management tool for the rehabilitation and reconstruction of highways. The model is beneficial for the highway agencies especially during the planning and design stages when the resulting analysis can be used to optimize pavement, construction, and traffic operations. It is also useful for design and construction engineers, consultants, and paving contractors in providing cost savings by comparing various alternatives during estimating and project control stages.

2. CA4PRS SOFTWARE OVERVIEW

CA4PRS is a production analysis tool designed to estimate the maximum probable length of highway pavement that can be rehabilitated or reconstructed given the various project constraints (Lee 2000). As summarized in Table 1, the CA4PRS model evaluates “what-if” scenarios with respect to rehabilitation production by comparing the following input variables (alternatives):

- *Pavement strategy*: PCC reconstruction, crack and seat PCC and asphalt overlay (CSOL), or full-depth asphalt concrete replacement (FDAC).
- *Construction window*: nighttime closures, weekend closure, continuous closure, or combinations of the above.

- *Lane closure tactics*: number of lanes to be closed for rehabilitation (i.e., partial or full closures).
- *Material constraints*: mix design and curing time for concrete or cooling time for asphalt.
- *Pavement cross section*: thickness of new concrete or asphalt concrete.
- *Concrete pavement base types*: lean concrete base (LCB) or asphalt concrete base (ACB).
- *Contractor's logistical resource constraints*: location, capacity, and numbers of rehabilitation equipment available (batch plant, delivery and hauling trucks, paving machine).
- *Scheduling interfaces*: mobilization/demobilization, traffic control time, and activity lead-lag time relationships and buffer sizes.

Table 1 Categorized Major Parameters, Comparable in the CA4PRS Model

Category	Options	
Rehabilitation Strategies	Concrete Rehabilitation or Reconstruction (PCC)	
	Asphalt Concrete	CSOL (Crack Seat and Overlay)
		Full Depth AC (FDAC) Replacement
Pavement Cross-section	PCC	203-mm Slab
		305-mm Slab
		User defined cross-section
	CSOL and FDAC	Multiple lift of layers
Scheduling Constraints	Construction Windows	Nighttime closure
		Weekend closure
		Continuous closure
	Schedule Relationship	Mobilization / Demobilization
		Activity lead-lag relationship
	Curing Time (PCC)	4 hours (Fast-Setting Cement)
		12 hours (Type III PCC)
		User specified curing time
Lane Closures and Rehabilitation Sequences	Cooling Time (CSOL & FDAC)	Function lift thickness and weather
	PCC	Concurrent work method
		Sequential work method
	PCC and FDAC	Single-lane rehabilitation
		Double-lane rehabilitation
Contractor's Logistics and Resource Constraints	CSOL	Partial closure
		Full closure
	Demolition hauling trucks	Capacity and number per hour
	Paving material delivery trucks	Capacity and number per hour
	Batch plant	Capacity and number
	Paving machines	Speed and number

A powerful feature of CA4PRS is that it can be integrated with macro- and microscopic traffic simulation models to quantify road user costs during construction. This can help planners, designers, and construction and materials engineers determine which pavement materials/structures and rehabilitation strategies maximize production without creating unacceptable traffic delays. The rehabilitation strategies and associated input variables modeled in CA4PRS are described in the following sections.

3. REHABILITATION STRATEGIES MODELED

It is challenging yet necessary to define a typical or common pavement rehabilitation process when trying to model the process. There are numerous rehabilitation strategies that may be implemented and are contingent upon: pavement materials, lane closure tactics, and contractor's resource constraints. Consultation with agencies and contractors led us to focus on and incorporate three common rehabilitation strategies into CA4PRS:

- *PCC reconstruction*: remove the old pavement and rebuild with PCC slab and optional pavement base structure.
- *CSOL rehabilitation*: crack and seat the old PCC pavement and overlay with new AC pavement.
- *FDAC replacement*: remove the old pavement and replace with full-depth AC pavement.

The number of traffic lanes in one direction of a typical urban freeway was assumed to be four for the sake of simplicity. Since most passenger lanes (P1 and P2) are generally in good condition, it furthermore was assumed that only the two outer truck lanes (T1 and T2) will be rebuilt in each direction in the PCC reconstruction and FDAC replacement strategies, as per LLPRS practice. In the case of CSOL rehabilitation, the whole freeway (i.e., main traffic lanes including median and outside shoulder) is assumed to be subject to rehabilitation. Details on rehabilitation methodologies and design variables for each rehabilitation strategy as an individual module in CA4PRS are summarized below.

3.1 PCC Reconstruction Strategy

3.1.1 Pavement Design Alternatives

The PCC reconstruction module in CA4PRS incorporates the following pavement design-related criteria (Lee et al. 2000):

- New pavement cross-sections
- Concrete mix design for new PCC slab
- The width of the outside truck lane

Three alternative new pavement cross sections – 203 mm (8-inch), 254 mm (10-inch), and 305 mm (12-inch) – are included in the PCC analysis module. The existing slab is assumed to be 203 mm thick (typical California situation). The latter two PCC slab designs (254 mm or 305 mm) will require replacing the existing base with a new thicker (150 mm) base, as illustrated in Figure 1. The user can also create his/her own cross-section profile if the default cross sections in the CA4PRS menu are not applicable for the project. The user can also enter in any additional demolition depth that might be necessary to comply with new height clearance requirements for bridge underpasses or overpasses.

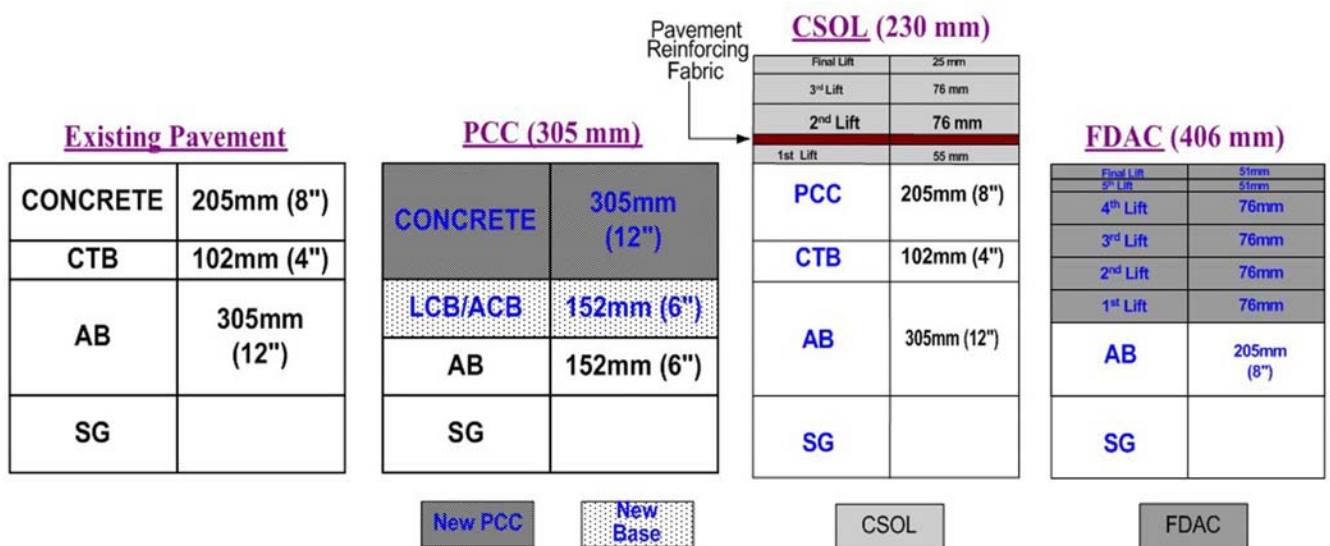


Figure 1. Examples of typical pavement cross-section changes for PCC, CSOL, and FDAC

In the PCC analysis module there are three default concrete mix designs to choose from: 4-, 8-, and 12-hour curing time mixes. Fast setting hydraulic cement concrete (FSHCC) or early-age strength Type III PCC products can quickly achieve traffic opening strengths of 2.8 MPa (400 psi) in California. This allows extra paving time that cannot be attained when using ordinary PCC. A user-defined concrete curing time is also allowed in the model.

The user has two options for the width of a new outside truck lane (T2): regular width (3.7 m) tied to the concrete shoulder, or widened truck lane (4.3 m).

3.1.2 Reconstruction Methodologies

Four combinations of construction operation sequence and lane closure tactics are included in the PCC analysis module: concurrent single-lane, sequential single-lane, concurrent double-lane, and sequential double-lane rehabilitations. The concurrent methods refer to the simultaneous undertaking of demolition of the existing slab and new slab and base paving operations. In the sequential methods slab

paving starts only after the demolition and base paving are completed. When performing both operations concurrently, interruptions between construction equipment (e.g., loader, hauling trucks, paving machine, and delivery trucks) can be avoided or minimized by providing the demolition and paving activities with their own access lane. In the sequential methods the demolition and paving activities share one lane for construction access one after the other, thus leaving one more lane open for freeway traffic than in the concurrent scenario. The shoulder is not assumed to be a reliable access lane in urban environments because it may be less than 3 m wide, adjacent to sound walls, or not continuous.

The two existing truck lanes can be paved either one-by-one or both lanes at once. Both single-lane paving and double-lane rehabilitation are applicable for both concurrent and sequential methods. Washington State Department of Transportation reported that higher productivity was observed when two lanes were paved simultaneously (Washington State Department of Transportation@ 2002). Double lane paving may have other advantages: simpler installation of tie bars and better quality control and long-term performance in the longitudinal joint.

3.2 CSOL Rehabilitation Strategy

3.2.1 Pavement Design Alternatives

In California, the CSOL rehabilitation involves placing three to five new AC layers on top of the cracked and seated PCC pavement (Figure 1). To slow the propagation of cracks, it is a common practice to install a pavement reinforcing fabric saturated with tack coat while the first AC layer is still hot. CSOL's major advantage is that it does not require removal of the existing PCC slabs, unlike the PCC reconstruction or FDAC replacement strategy. However the AC overlay cannot be placed underneath bridge overpasses unless there is adequate clearance between the freeway and the bridge. Another constraint is that CSOL usually requires that all lanes and shoulders be paved to maintain uniform elevation.

In the CSOL analysis module the user is able to create a project-specific cross section by specifying the total number of AC layers (lifts) required and the thickness of each layer. As illustrated in Figure 1, the typical Caltrans LLPRS design calls for four AC layers with thickness varying from 200 mm (8-inch) to 250 mm (10-inch). "MultiCool" is a numerical simulation program that calculates the AC cooling time for multi layer AC paving. It is embedded in CA4PRS to check the suspension of the paving operation due to the cooling time (Timm et al. 2001).

3.2.2 Rehabilitation Methodologies

Two lane closure tactics are permitted in the CSOL analysis module: CSOL full-closure and CSOL half-closure (Lee et al. 2002a). In the case of CSOL full-closure, one direction of the freeway is completely closed off for rehabilitation and traffic is switched to the other side of construction through median crossovers, utilizing counter-flow traffic. The main lanes and shoulders are overlaid completely layer-by-layer and lane-by-lane on one side of the freeway within a closure. Usually the paving operation alternates the sequence of paving lanes to minimize waiting time.

Half-closure CSOL requires closing down only two out of four lanes in one direction during a closure. This allows two lanes to be open to traffic in the direction of the rehabilitation and four lanes of traffic in the opposite direction. Traffic would be separated from the construction work zone by a moveable concrete barrier (MCB). This half-closure option has two sub-options: 1) CSOL half-closure with full-completion, where part of the AC layers are placed on two lanes, and then traffic is shifted to the newly paved lanes while the other two are paved, and this process is repeated until the section is completed; and 2) CSOL half-closure with partial-completion, where the first bottom AC layers are overlaid at the first closure and the remaining top layers are completed at the subsequent closure.

3.3 **FDAC Replacement Strategy**

The FDAC replacement strategy requires complete removal of the PCC and partial trimming of the aggregate base to accommodate the specified depth of the new AC pavement. Similar to the CSOL analysis module, the FDAC analysis module allows the user to input project-specific AC cross sections. In Caltrans LLPRS projects a rich bottom AC layer will normally be placed on top of the re-compacted Aggregate Base (AB), followed by 5 or 6 AC layers paved sequentially, with total thickness ranging from 330 mm (13-inch) to 406 mm (16-inch), as illustrated in Figure 1.

The FDAC analysis module includes two lane closure tactics: single-lane or double-lane rehabilitation. A benefit of the double-lane rehabilitation is that the multiple AC layers are interlocked by overlapping the longitudinal joints between adjacent lanes. The single- and double-lane rehabilitation concept for the FDAC replacement is similar to the PCC reconstruction methodology. Following a common AC paving practice, the double-lane rehabilitation option for the FDAC replacement does not specify paving both lanes in one pull, unlike PCC reconstruction.

4 CA4PRS COMPUTATIONAL BACKGROUND

4.1 CA4PRS Computational Process

Typical input procedure and analytical processes of CA4PRS are:

1. Choose the analysis mode: deterministic or probabilistic.
2. Input the total scope (lane-km) of the rehabilitation project.
3. Select a rehabilitation strategy: PCC reconstruction, CSOL rehabilitation, or FD AC replacement analysis modules.
4. Define the new pavement cross section: slab and base thickness (PCC) or layer profile (AC).
5. Set the concrete curing time (PCC) or AC cooling time (or let the MultiCool software calculate cooling times interactively).
6. Decide a construction window (closure timing and length): for example, 10-hour nighttimes, 55-hour weekend, or 72-hour weekday closures.
7. Define activity lead-lag relationships (start-to-start, finish-to-start, etc.) between major operations: mobilization, demobilization, and minimum time interfaces between operations.
8. Select rehabilitation sequences and lane closure tactics: concurrent vs. sequential and single-lane vs. double-lane rehabilitations.
9. Input contractor's logistical resources (crew, equipment, and plants) for major operations. The number of hauling and delivery trucks per hour should take into account the minimum cycle for supply and haul trucks. (Our prior research has found that loading or discharging trucks is usually the critical productivity constraint).

Based on these inputs and constraints, CA4PRS performs the following computations:

10. Quantify material volumes for the major operations: demolition, AC paving, or PCC paving.
11. Utilize a simplified CPM (Critical Path Method) scheduling analysis to calculate available durations for the main operations.
12. Quantify the production capability of each resource input, and apply a linear scheduling technique to identify the constraining resource and consequently the maximum production capability.
13. Provide consistency checks on the main CA4PRS outputs including:
 - Maximum rehabilitation production (lane-km) per closure
 - Total number of closures and duration needed to finish the whole project scope
 - Constraining resource and minimally needed resource profile

- Balanced time allocation between the demolition and paving operations

4.2 CA4PRS Computational Platform

The CA4PRS software runs on Microsoft Windows 95/NT4.098/2000/XP™ or higher operating systems. It is developed in Microsoft Visual Basic 6.0 and utilizes a Microsoft Access 2000 database as the back-end for data storage, though it does not require Microsoft Access installed to run the software. CA4PRS utilizes a number of third-party, royalty free tools to enhance the user friendliness, versatility of the user interfaces, and presentation quality of the program. It has a multiple-document interface (MDI), similar to Microsoft Excel or Microsoft Word, which enables multiple projects and analyses to be opened, viewed and compared simultaneously. CA4PRS is designed for project level analysis and each project analysis must have a unique identifier as the primary key in the CA4PRS database for storing and retrieving all related information.

As illustrated in Figure 2, CA4PRS employs a systematic menu structure that groups menu items in an intuitive manner and provides context sensitive online help and a user manual. Its hierarchical structure provides extensive graphical and tabular outputs and incorporates a report feature that documents the analysis input and output for printing or saving as an Adobe Portable Document Format (PDF) or Rich Text Format (RTF) file. CA4PRS provides seamless transition between deterministic and probabilistic analysis modes, as described in the following section, and the user can easily transfer project data between the two analysis modes.

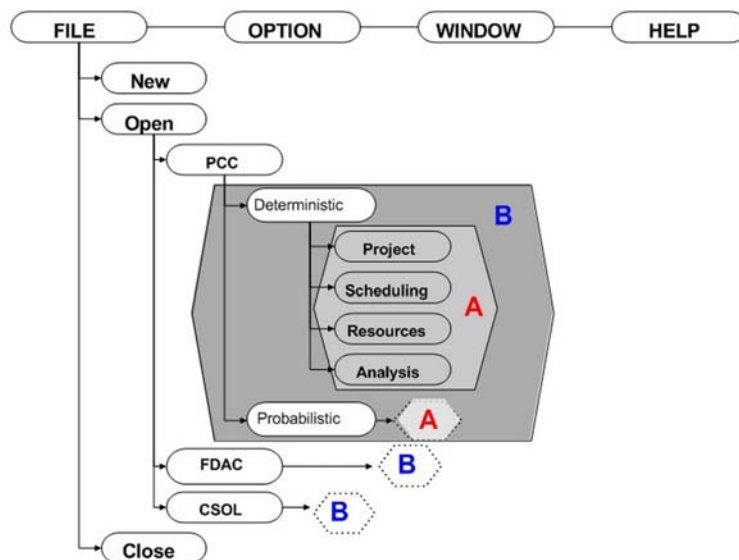


Figure 2. CA4PRS menu structure and analysis hierarchy

4.3 Deterministic and Probabilistic Analysis Modes

CA4PRS can perform both deterministic and probabilistic analysis. In the deterministic analysis mode the input parameters including resource and scheduling constraints (activity lead-lag time relationships) are treated as constants without any variations. This mode seeks the straightforward maximum pavement amount (distance) that can be rebuilt within the construction closure windows under the given project constraints.

The probabilistic (stochastic) mode treats input parameters as random variables. Each variable can be described using an appropriate statistical distribution; the options are uniform, normal, log normal, beta, geometric, triangular, truncated normal and truncated log normal. This mode permits the user to review the likelihood of achieving different pavement rehabilitation production rates, utilizing Monte Carlo simulation.

5 CA4PRS INPUT WINDOWS

The user starts an analysis by either creating a new one or by opening an existing one, with four input tab window prompts:

- *Project details window*
- *Scheduling window*
- *Resource profile window*
- *Analysis window*

The input configurations of the deterministic and stochastic modes are similar except that the former asks the user to specify absolute values for the uncertain variable (constant numbers). The stochastic model provides the user a list library of probability distribution functions to choose from.

5.1 Project Details Window

The project details window prompts the user to input the basic textural information on a proposed project, including identifying project descriptions, route name, post (station) miles, location, etc. In the project objective cell the user specifies the project scope by typing in total lane-km (or mile) to be rehabilitated as shown in Figure 3. This user-specified project objective (goal) then acts as the baseline to compute total number of closures required based on the rehabilitation production estimation of each scenario to be calculated at the end of the analysis. When a number of alternative scenarios are considered for the same project, the distinct features of each alternative can be recorded under the “Project Notes” portion of the window.

Constructability and Productivity Analysis

File Options Window Help

CSOL Depth Deterministic - 710_CSOL_55-H Wee...

Project Identifier: 710_CSOL_55-H Weekend

Project Details | Scheduling | Resource Profile | Analysis

Project Description: Caltrans AC (CSOL) Demonstration Project

Analyst Name: EB Lee Analysis Date: 5/13/2002

Route Name: I-710

Begin KM: 5.00 End KM: 10.00

Objective (lane-km): 21.00 Unit: ☐ Imperial ☒ Metric

Location: Long Beach, CA

Project Notes: From PCH to I-405
3 lanes each direction
Add shoulders both sides

Save Close

Figure 3. Project details input window in the CSOL deterministic mode

5.2 Scheduling Window

Shown in Figure 4 is the probabilistic scheduling window (with the PCC analysis module shown for example). The scheduling aspects of the project are categorized into three sub-groups: mobilization/demobilization variables, construction closures (windows), and activity lead-lag time relationships. A certain minimum time will be needed for mobilization and demobilization purposes such as site preparation, cleaning-up, and, more importantly, traffic control for the construction.

As illustrated in Figure 4, three alternative time frames (construction windows) are available to the user: nighttime (typically weekdays), weekend, and continuous closures. The continuous closure has two sub-options to choose from: 1) continuous closure with daytime-only shift operations, with one or two crew shift(s) for a limited number of weekdays while the freeway remains closed throughout the whole period of rehabilitation; and 2) continuous closure with continuous operations, which means fast-track accelerated construction with round-the-clock operations using two or three rotating crew shifts.

The screenshot displays the 'Constructability and Productivity Analysis' software interface. The main window is titled 'PCCP Probabilistic - I-15 72-H Weekday (Final)'. It features a menu bar with 'File', 'Options', 'Window', and 'Help'. Below the menu bar, there are tabs for 'Project Details', 'Scheduling', 'Resource Profile', and 'Analysis'. The 'Scheduling' tab is active, showing fields for 'Mobilization (Hours)' (3.0), 'Demobilization (Hours)' (13.7), and 'Construction Start Date' (3 / 1 / 2004). A 'Construction Window...' button is visible. Below these fields, there are sections for 'Log Times for Sequential Working Method' and 'Log Times for Concurrent Working Method'. The 'Sequential Working Method' section includes 'Demolition to New Base Installation (Hours)' (14.0) and 'New Base Installation to PCCP Installation (Hours)' (6.0). A checkbox 'PCCP Installation can begin before New Base Installation is Complete' is present. The 'Concurrent Working Method' section is currently empty. A 'Save' button is at the bottom right of the main window. Overlaid on the main window is the 'Construction Window Settings' dialog box. This dialog has four sections: 'Weekend Closure' (Start Time on Friday: 10:00 PM, End Time on Monday: 05:00 AM, Available Hours: 55.0), 'Nighttime Closure' (Start Time on First Day: 07:00 PM, End Time on Next Day: 05:00 AM, Available Hours per Day: 10.0), 'Continuous Closure/Continuous Operation' (Start Time on First Day: 12:00 AM, No. of Continuous Work Days: 3.0, Available Hours per Day: 24.0), and 'Continuous Closure/Shift Operation' (Daily Start Time: 06:00 AM, No. of Continuous Work Days: 6.0, Available Hours per Day: 16.0). The dialog has 'Save' and 'Close' buttons at the bottom.

Figure 4. Scheduling input window in the PCC probabilistic mode

5.3 Resource Profile Window

The contractor's logistics and resource constraints are two of the most decisive factors in rehabilitation production, especially in fast-track urban highway rehabilitation where the space and access for construction equipment is often limited. As illustrated in Figure 5, the user inputs the number and capacity of the available equipment and plants. Some resource inputs will require prior knowledge, experience and personal judgment from the user. For instance, the user should input a reasonable number of demolition hauling trucks per hour by taking account of the expected loading cycle time of the demolition and turn-around time of the trucks between site and dumping area.

Full Depth Probabilistic - 710_Full Depth_55-H Weekend

Project Identifier: 710_Full Depth_55-H Weekend

Project Details | Scheduling | Resource Profile | Analysis

Dump Truck (Demolition)

Rated Capacity (kg): 22000.0

Trucks per Hour: 10.0

Packing Efficiency: 0.70

Number of Team: 1.0

Team Efficiency: 1.00

Batch Plant

Capacity (tonne): 400.0

Number of Plants: 1

Semi Bottom Truck for Asphalt

Rated Capacity (kg): 24000.0

Trucks per Hour: 15

Packing Efficiency: 1.00

Paver

Non Paving Travel Speed (kph): 29.0

Define Probability Input

Probability Function: Normal

Mean: 15

Std. Dev.: 2.0

Save Close Ok Cancel

Figure 5. Resource profile input window in the FDAC probabilistic mode

5.4 Analysis Window

Figure 6 and 7 illustrate the analysis input windows for the PCC and FDAC deterministic mode, respectively. Here the user selects and controls the following input categories for the PCC analysis module, as an example:

- Construction windows
- Rehabilitation sequence with respect to lane closure tactics
- Concrete curing time
- Pavement cross section changes
- Truck lane width

PCCP Deterministic - I-15 72-H Weekday (Final)

Project Identifier: I-15 72-H Weekday (Final)

Project Details | **Scheduling** | Resource Profile | Analysis

Construction Window

☐ Weekend Closure
☐ Nighttime Closure
☒ Continuous Closure/Continuous Operation
☐ Continuous Closure/Shift Operation

Working Method

☐ Sequential Single Lane (T1)
☐ Sequential Single Lane (T2)
☐ Sequential Double Lane (T1+T2)

Curing Time

☐ 4-Hours
☐ 8-Hours
☒ 12-Hours
☐ User Defined: 10.0 Hours

Section Profile

☐ 203 mm (8 inches)
☐ 254 mm (10 inches)
☐ 305 mm (12 inches)
☒ User Defined: PCCP (mm) 290.0
Treated Base (mm) 152.4
☐ Additional Demolition: Depth (mm) 100.0

Construction Plan

☒ Sequential Single Lane (T1)
☐ Sequential Single Lane (T2)
☐ Sequential Double Lane (T1+T2)
☐ Concurrent Single Lane (T1)
☐ Concurrent Single Lane (T2)
☐ Concurrent Double Lane (T1+T2)

Diagram: S1 | P1 | P2 | T1 | T2 | S2

Buttons: Open, Access, Paving

Buttons: Analyze..., Compare..., Close

Figure 6. Analysis input window in the PCC deterministic mode

For each input category, a drop-down list of values or check box options is available. To analyze and compare various options, the user can choose one or more variables. As shown in Figure 7, the asphalt (CSOL and FDAC) analysis window also allows the user to enter estimated cooling times for each AC lift or choose the option to run the MultiCool software instead.

Full Depth Deterministic - 710_Full Depth_55-H Weekend

Project Identifier: 710_Full Depth_55-H Weekend

Project Details | **Scheduling** | Resource Profile | Analysis

Construction Window

☒ Weekend Closure
☐ Nighttime Closure
☐ Continuous Closure/Continuous Operation
☐ Continuous Closure/Shift Operation

Working Method

☒ Single Lane Paving (T1)
☐ Single Lane Paving (T2)
☐ Double Lane Paving (T1+T2)

Section Profile

Define... ☒ Profile A
Define... ☐ Profile B

☒ Additional Demolition: Depth (in) 6.5

Lane Widths

T1 Width (ft): 17.7
T2 Width (ft): 12.0

Cooling Time Analysis

☒ User Specified
☐ MultiCool Computed: MultiCool Data...

ACP Layer Definition - Profile A

Lift Number	Lift Thickness (in)	Lift Name	Lift Cooling Time (hour)	Paver Speed (mph)
4	3.00	PBA-6a	3.00	2.75
3	3.00	AR-8000	3.00	2.80
2	3.00	AR-8000	2.00	2.80
1	3.70	Rich Bottom	1.00	2.09
Total: 12.70			Average: 2.25	Average: 2.61

Buttons: Insert, Delete, Ok, Cancel

Figure 7. Analysis input window in the FDAC deterministic mode

6 CA4PRS OUTPUTS

As mentioned earlier, CA4PRS produces either a single or multitude of analysis results, depending on the number of input options the user selects. For example, if the user elects to consider two concrete curing time options (4-hour and 12-hour), two rehabilitation sequence options (sequential single-lane and concurrent double-lane), and two cross section profiles (203 mm and user defined) for the 55-hour weekend closure in the PCC analysis module, a total of 8 (2x2x2) analysis results, each in a separate output window, will be generated once the user clicks the ‘Analyze’ button.

6.1 Deterministic Outputs

In deterministic mode, the output is presented in two parts: Production Details and Production Chart. Included in the production details screen are the user input summary and the main analysis results, as shown in Figure 8.

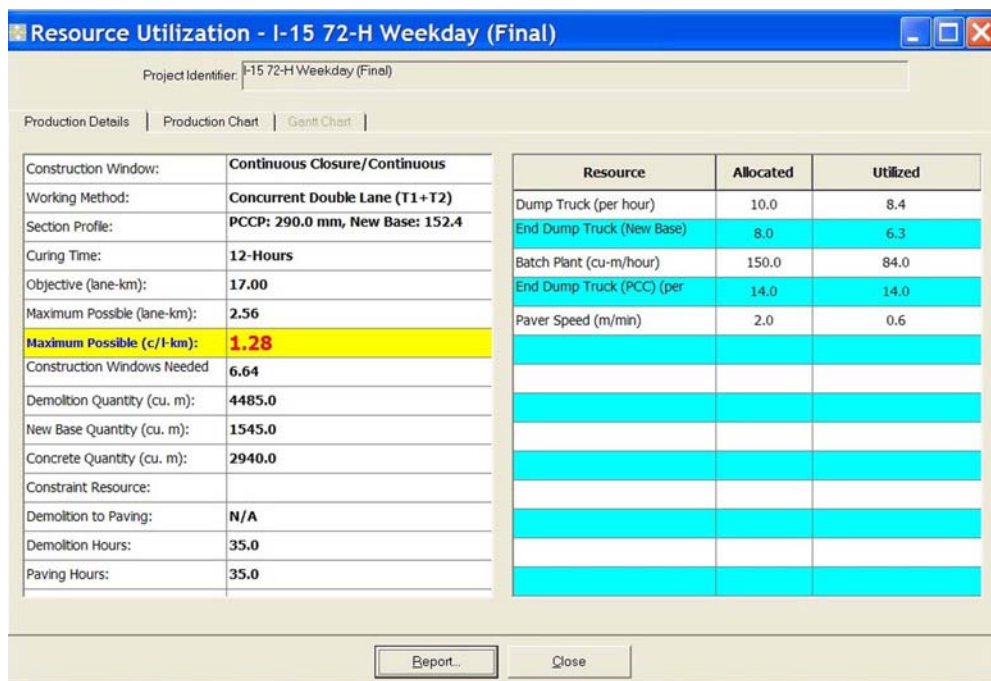


Figure 8. Output screen generated by PCC deterministic (table) mode

The main results are the maximum production of each rehabilitation scenario analyzed in terms of lane-km, and the total number of closures to finish the whole rehabilitation project scope (objective) based on the maximum production of the each scenario. Some additional information is also provided in the outputs, including a summary of material volumes for the major operations like demolition, slab paving, and base paving. The main results of the CPM scheduling analysis are provided as well; i.e., the

optimally balanced maximum duration of the demolition and paving activities within a given closure time limit. Figure 9 illustrates the production chart screen representing a “line of balance schedule” where the linear progress of the main rehabilitation operations is plotted against the time.

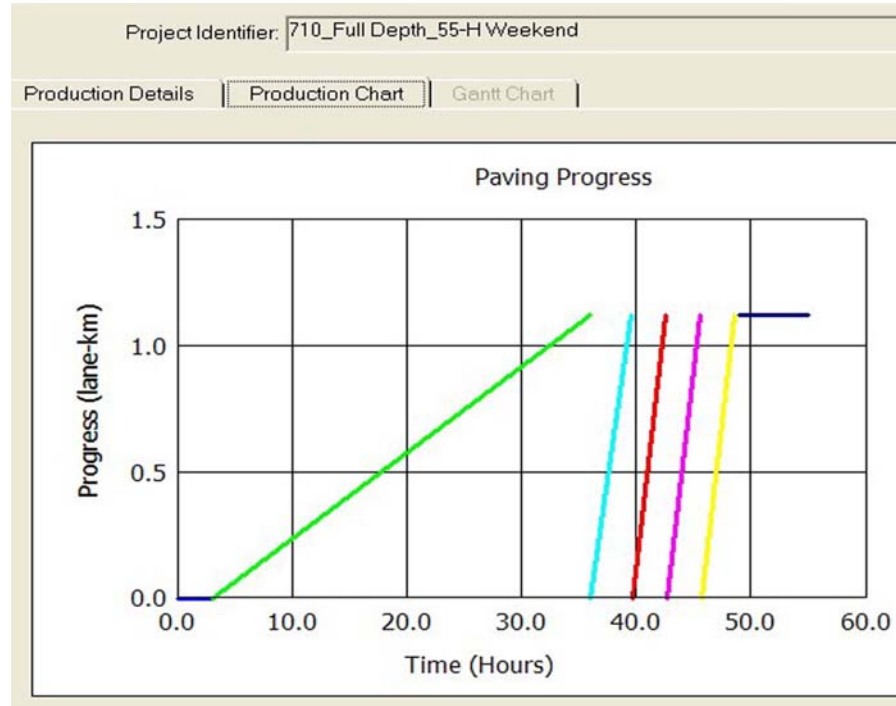


Figure 9. Line of balance schedule chart for FDAC

One of the most useful features of the CA4PRS outputs, especially from the contractor’s point of view, is identifying which input equipment constrains the operations. A list of input resources, with a comparison of the input number and number minimally needed, is tabulated in the project details output window; see Figure 8.

When the user checks multiple options in each category in the analysis window, the number of output windows could be too large for effective comparison of all the analyzed scenarios at once. To avoid this inconvenience, a simplified comparison table can be generated. It summarizes the main inputs and outputs in a hierarchical manner: starting with the construction window, then the section profile, the rehabilitation sequence, etc.

6.2 Probabilistic Outputs

One main difference between the probabilistic and deterministic modes is that the probabilistic outputs show a plot of the distribution of maximum production as a result of the Monte Carlo simulation, as illustrated in Figure 10. The probabilistic output, as a normalized distribution according

to the Central Limit Theorem (Moder 1983), represents the most likely maximum production as a mean, and productions at -0.5 standard deviation and +0.5 standard deviation as lower and upper bounds, respectively. Despite requiring more input information and more time to run, the stochastic formulation provides a more realistic estimation and comprehensive description of the rehabilitation production. One other advantage of the probabilistic analysis is that it permits the user to see the relative contribution of the probabilistic input variables to the rehabilitation production as a whole, in the sensitivity “tornado” chart, as shown in Figure 10.

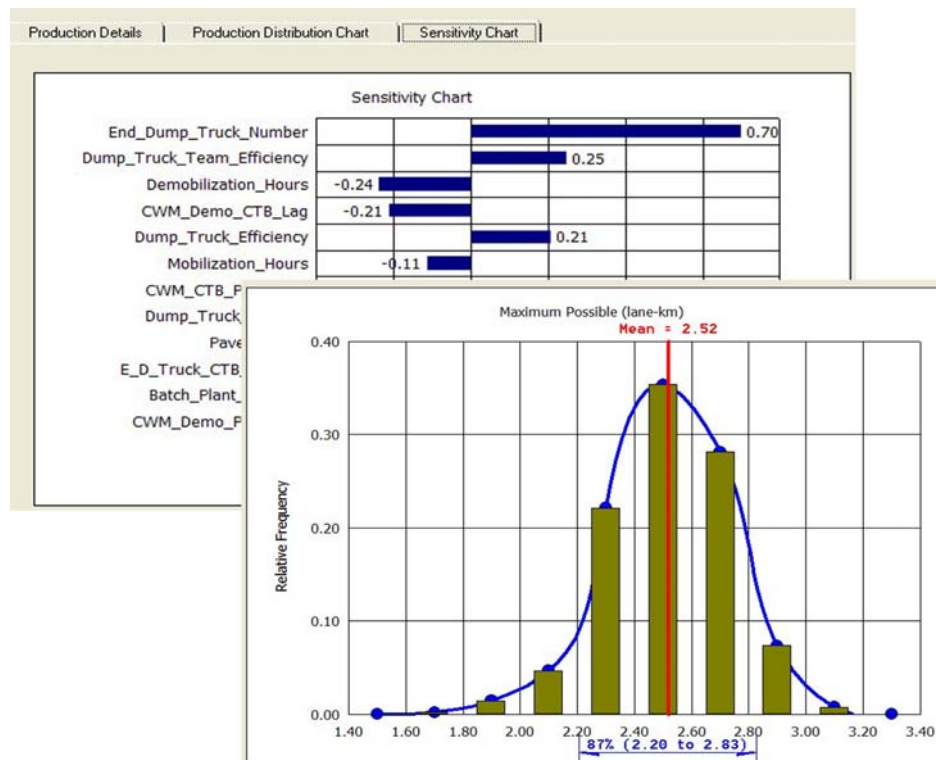


Figure 10. Sensitivity chart and the most likely maximum production rate by the PCC probabilistic (graph) analysis

7 CA4PRS CASE STUDIES

The CA4PRS software has been verified and applied on several numbers of Caltrans LLPRS projects, as summarized below.

7.1 CA4PRS Validation on I-10 Project

A case study was performed for the validation of CA4PRS on the first concrete LLPRS project on Interstate 10 near Pomona. This job consisted of 2.8 lane-km successfully rebuilt with one 55-hour

weekend closure (Friday 10 p.m. – Monday 5 a.m.) in late 1999 (Lee et al. 2002b). The highway segment, having four-lanes in each direction, was built in the early 1960's and had a high concentration of deteriorated concrete pavement due to traffic volumes of 240,000 ADT with approximately 9 percent heavy trucks. Two of the four lanes remained open while the inner truck lane (T1) in the eastbound direction was rehabilitated. The outer truck lane (T2) was used for construction access. The contractor used the "PCC concurrent single-lane paving" method. Demolition and concrete paving occurred simultaneously to replace the 230 mm of old slab with a new slab using fast-setting concrete. Under the incentives/disincentives clause in the contract, the contractor was awarded a \$500,000 bonus payment for successful completion of the PCC rehabilitation within the 55-hour weekend closure.

The lower bound production of 2.8 lane-km, predicted with the confidence level of 68 percent in the CA4PRS probabilistic mode, was identical to the actual production performance monitored by the research team during the weekend closure. The contractor encountered the lower production limit of 2.8 lane-km only because of several resource problems, including a main batch plant breakdown for about 4 hours. The CA4PRS probabilistic analysis estimated a best case (upper bound) scenario of 3.4 lane-km production.

7.2 CA4PRS Application on I-710 Project

The CA4PRS software was next tested on an asphalt LLPRS project on Interstate 710 in Long Beach. A 4.4-km stretch of the freeway (total of 26.3 lane-km) was rehabilitated successfully with long-life AC in eight 55-hour weekend closures, two weekends earlier than initially planned by Caltrans District 7 (Lee et al. 2003a). First opened in 1952, this stretch of I-710 carries more than 164,000 ADT, including 13 percent heavy trucks during weekdays. The project had four FDAC sections located under the four bridge overpasses, where the existing PCC pavement structure was excavated and removed to a depth of 625 mm, and replaced with 325 mm of AC. The pavement between the FDAC sections received 230 mm of CSOL. Caltrans applied "counter-flow traffic" controls during construction ("full-closure and full-completion AC rehabilitation" method).

For this scenario CA4PRS estimated that the maximum production capability of a 55-hour weekend was about 1.3 km of the CSOL section and one FDAC section (about 0.4 km). Prior to starting construction, the CA4PRS analysis results confirmed that the contractor's goal of completing the main rehabilitation work in eight weekend closures was realistic. However, the CA4PRS analysis also warned that the contractor's initial plan of rehabilitating about two FDAC section (about 0.8 km,

basically two overpasses) and 1.3 km of the CSOL section per weekend was overly optimistic. (This optimism may have been encouraged by an incentive provision that offered the contractor \$100,000 per unused weekend closure, cap at \$500,000.) The contractor revised his production plan based on the production levels recommended by the researchers.

The contractor's actual production performance measured in the construction monitoring study by the research team was within about 5% of the CA4PRS production estimates. In addition, the number of demolition hauling trucks (an average of 10 trucks per hour) and hot mix asphalt delivery trucks (12 trucks per hour on average) predicted by CA4PRS was similar to the contractor's eventual fleet.

7.3 CA4PRS Integration on I-15 Project

The next case study is on the third Caltrans LLPRS project to rebuild a 4.2-km stretch (total of 17 lane-km, two truck lanes in both directions) of Interstate 15, scheduled to begin fall 2004. This highway, near Devore in San Bernardino County, carries 110,000 ADT on weekends (leisure traffic between Los Angeles and Las Vegas). A full closure approach ("concurrent double-lane rehabilitation") strategy was selected. The Berkeley research team was involved at the outset to assist in preparing an integrated analysis of pavement materials and design, construction logistics, and traffic operations. The goal was to determine the most economical reconstruction closure scenario. (Lee et al. 2003b and 2003c). The existing pavement structure consisted of 203 mm (8-inch) PCC slabs, 102 mm (4-inch) CTB, and 450 mm (18-inch) AB. This old pavement is to be replaced with 290 mm (11.5-inch) of plain, jointed, and doweled concrete slabs utilizing the early strength Type III PCC (so-called "12-hour mix") and 152 mm (6-inch) of asphalt concrete base (ACB).

The concept of total cost, integrating closure schedule, road user cost, and construction and traffic handling costs, was used for the closure strategy selection criteria. The CA4PRS software was used for scheduling analysis as a baseline. The demand-capacity model (Highway Capacity Manual), and macroscopic (FREQ) and microscopic (Paramics) traffic simulation models were utilized for traffic delay analysis. Caltrans decided to implement eight 72-hour weekday closures with round-the-clock operations based on the CA4PRS schedule analysis. The analysis demonstrated that the 72-hour closure scenario had 77 percent less total closure time, 34 percent less road user cost, and 38 percent less agency cost when compared with the traditional nighttime closures (Lee et al. 2003c).

8 CONCLUSIONS

CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) software is structured and designed to predict the maximum amount (distance) of highway that can be rehabilitated or reconstructed given various parameters, such as closure scenarios, pavement materials and design, lane closure tactics, schedule interfaces, and contractor's logistics and resources. The software is a useful constructability analysis tool for transportation agencies and contractors who want to evaluate "what-if" scenarios at each stage of the pavement rehabilitation project: feasibility/planning, design, and construction. It provides a construction schedule baseline for the integration of design, construction, and traffic, all of which are essential for the selection of the most economical pavement rehabilitation strategies. The CA4PRS model can be integrated with traffic analysis tools and when combined with a traffic model, CA4PRS software can help determine which pavement structures and rehabilitation strategies maximize on-schedule construction production without creating unacceptable traffic delays.

The software has been verified on the Caltrans I-10 Pomona project where Concrete Long-life pavement was built in a 55-hour weekend closure. It has been used to evaluate plans for the Caltrans I-710 Long Beach project where Asphalt Long-life pavement was built in eight 55-h weekend closures.

Further enhancements and upgrades are currently underway so that the enhanced CA4PRS model will cover even more rehabilitation strategies such as a continuous reinforced concrete pavement strategy.

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